Draft force requirements of a dual bent blade subsurface tillage implement

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Abstract: Decreasing draft force of tillage tools is always one of the important concepts in tillage operation. According to structure properties of bent leg, in this research, two upward and backward dual bent blade subsurface tools with two rake angles of 7.5 and 15 degree and two bend angles of 10 and 20 degree were developed and draft force, soil disturbance area and specific draft were compared in two soil moisture content levels of 0.7 and 0.9 of plastic limit (PL). The effect of soil moisture content was not significant on any of the measured variables. The draft force of the subsurface tools was increased with increasing rake and bend angles of blade. The least mean of draft force was achieved in forward dual bent blade subsurface tool with bend angle of 10 degree and rake angle of 7.5 degree. The effect of rake angle and subsurface type were significant on soil disturbance area. The specific draft was increased with increasing bend angle. The forward dual bent blade subsurface tool had a better yield with decreasing specific draft and increasing soil disturbance area.

Keywords: rake angle, bent blade, subsurface tillage, soil disturbance area, dual bent blade

Citation: Salar, M. R., A. Esehaghbeygi, A. Hemmat, and H. Kargarpour. 2017. Draft force requirements of a dual bent blade subsurface tillage implement. Agricultural Engineering International: CIGR Journal, 19(1): 74–80.

1 Introduction

The fuel consumption and tractor draft power for tillage tool is a limiting factor in soil. Draft force is the parameter which is used to determine the tractor's power requirement. Higher draft force means higher tractor power requirement (Arvidsson and Hillerström, 2010; Hasimu and Chen, 2014). Researches carried out in line with a reduction in tensile strength of tillage tools has led to the design and construction of new devices called bent leg and Para plow. These tools with the specific structure ruptured the soil structure while did not rummage the soil and on the other hand, required less traction force (Harrison, 1988). Harrison and Licsko (1989) compared the effects of two bent angles (30 and 45 degree) and two rake angles (0 and 15 degree) on bent leg plow soil reaction. They stated that at rake angle of zero degree, friction caused between both the upper and lower surfaces of the blade increased the forces acting on the blade. The plow penetration into the soil was better at the rake angle of 15 degree and its penetration was less at zero degree rake angle. Majidi and Raoufat (1997) showed that the traction strength was the least in the rake angle of 7.5 degree using a single right rotation bent leg plow with the bent angle of 30 degree and increasing depth, the draft in bent leg was more compared with moldboard plow, while its specific draft was significantly lower. Cross sectional area of disturbed soil was the maximum at the rake angle of 15 degree and the draft was the minimum when working with 7.5 degree of rake angle. The studies of Durairaj and Balasubramanian (1997) revealed that the bent leg plow with rake angles of 9 and 15 degree had the minimum draft and maximum penetration into the soil. The maximum of soil failure was obtained at the lowest bent angle and highest rake angle led to an increase in draft force. Esehaghbeygi et al. (2005) showed that in forward bent leg plow with decreasing the width of the blade and increasing depth in line with increase in rake

Received date: 2015-11-30 **Accepted date:** 2016-11-21

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angle leaded to more vertical stress on the soil that draft force was increased while increasing soil disturbed area. The effect of various rake angles (10°, 15°, 20°, and 25°) was investigated on draft and vertical forces of chisel plow and increasing the rake angle led to decrease in vertical force while the draft force declined until the rake angle of 15° and then increased (Jafari et al., 2011).

The aim of this research was to design and evaluate a new tillage tool named double bent blade sub-surface for using in conservation tillage. The study planned to find the optimum geometry of this tool to have low energy consumption. The new tool was designed based on geometry and structure of bent leg plow.

2 Materials and methods

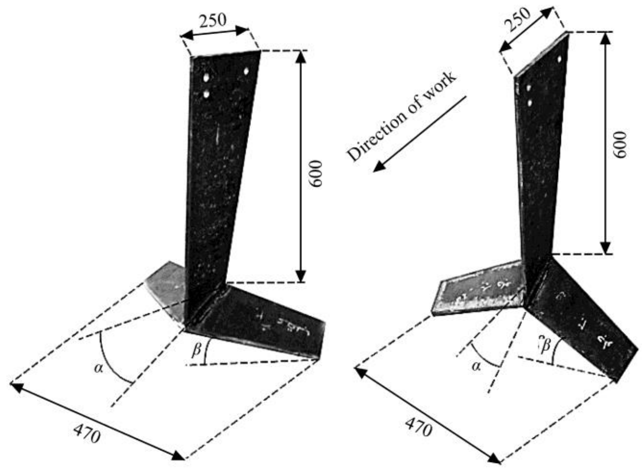
Two types of sub-surface tillage tools were designed and developed with bent blades forward and backward for using in conservation tillage and reducing energy consumption in tillage operation. The study was conducted at the Research Farm of Isfahan University of Technology (328310 N, latitude; 518230 E, longitude; and 1630 m above sea level) in central Iran. The soil of the experimental site was clay loam as presented in Table 1. The study field had been irrigated using the classic fixed sprinkler irrigation system and had barley stubble residues from the previous farming season. For the purposes of this study, the field was divided into two equal parts and each part was further divided into eleven plots based on the split plot experiment in a randomized complete block design. Nine plots 3 m wide and 50 m long were inside each block. For tractors to turn at the end of plots, an 8 m distance was left free between blocks.

Table 1 Analysis of clay loam soil at the experiment site

Property	Amount
Sand	20.2%
Silt	41.8%
Clay	38%
Plastic limit	20.3%
Dry bulk density	1.27 g cm^{-3}

The draft force, specific draft and soil distribution area were measured as the experimental variables while the soil texture, tillage depth (15 cm) and tractor forward speed (5 km h^{-1}) and the amount of the residuals in all plots were considered to be fixed. The tractor forward speed depends on the field conditions and drawbar power. The depth of tillage was controlled and kept constant by two depth wheels during tillage.

The performance of the two types of dual bent blade subsurface tillage tools, one backward blade (Figure 1a) and one forward blade (Figure 1b), were examined with the same width of 470 mm. The experimental tools were tested using two different rake angles, α (namely, 7.5° and 15°) and two bent angles, β (namely, 10° and 20°) at two different soil water contents (WC), 0.7 (13.6% db) and 0.9 (17.8% db) of plastic limit (PL). CK45 steel was chosen as the material of the tool, which had a high capability of heat treatment with thickness of 10 mm.



a. Backward b. Forward

Note: Dimensions are in mm, α and β are rake and bend angle, respectively.

Figure 1 Dual bent blade subsurface tillage tool

The draft force of the tillage tools were measured by RNAM standard method by means of drawbar dynamometer connected between two tractors. The dynamometer was attached to the driving tractor (front tractor) by a chine and the other hook was connected to the front of the tractor that was carrying the tillage tool (rear tractor) (Figure 2). The dynamometer and its chine were parallel to the farm surface and by moving the front tractor the total of draft force of tillage tool and the rolling resistance of rear tractor was recorded by a camera from dynamometer screen. Determining the rolling resistance of the carrying tractor, the tool brought out of the soil and in no-load condition the rolling resistance was measured and subtracted from the total draft in the previous step. The carrier tractors was manufactured by Massey Ferguson Tractor Co. model 285 with nominal power of 75 hp and the driving tractor was manufactured by John Deere Co. Model 3140 with a nominal power of 100 hp.

Figure 2 Condition of drawbar dynamometer between the two tractors

The width of soil disturbance area was the parameter involved in determining the optimum distance between two blades on a frame. In order to determine the area of soil failure cross sectional area in each treatment, soil cutting was created crossing by the tillage tool. Using Equation (1), the soil disturbance area of each trapezoidal area of the element was calculated using $(d_1+d_2)h/2$, where h was constant at 2 cm intervals (Salar et al. 2013)

$$A=(2\sum_{i=1}^{n}d_i)-(d_1+d_n) \quad (1)$$

where, A is soil disturbance area; d_i is the profile meter readings; and d_1 and d_n are the first and last profile meter readings in every section profile, respectively (Figure 3).

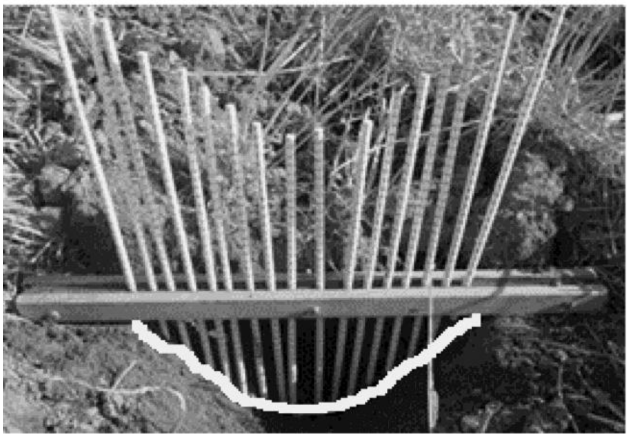


Figure 3 Using profile meter to measure soil disturbance area

In order to investigate the effect of experimental parameters on the measured variables, the mean comparison was based on factorial experiments (moisture, tool type, rake angle, bend angle). All the statistical analyses were performed using SAS 9.1 software. If the effect of any parameter was significant, the means were compared using the least significant difference (LSD) test at 5% significant level.

3 Results and discussion

The results of Analysis of variance (ANOVA) revealed that the effect of moisture content was not significant on the draft force of bent blade subsurface tillage tool (Table 2). The soil moisture had a small role on the draft force of the tools and increasing the moisture from 0.7 PL to 0.9 PL, the draft force only increased 0.6% (Table 3). It was expected that with increasing soil moisture, the tillage tool cut the soil easier and less force was required for soil failure (Dexter and Bird, 2001; Arvidsson et al., 2004; Sánchez-Giron et al., 2005; Arvidsson and Bolenius, 2006). On the other hand it was probable that with increasing soil moisture, integration enhanced between soil particles and caused coarse aggregate and increase in the volume of soil failure and ultimately led to increase in surcharge force and draft force (Dexter and Bird, 2001) that this trend was not observed in the results. Simple tillage tools pushed the soil in forward direction and the soil failed under compression and decreasing soil moisture the draft force increased due to increase in internal soil friction (Dexter and Bird, 2001; Arvidsson et al., 2004; Sánchez-Giron et al., 2005; Arvidsson and Bolenius, 2006) while the results showed that the dual bent blade subsurface tillage tool lifted the soil and put the soil under tension with releasing it. In this condition the difference between the surcharge forces was negligible in two moisture content of 0.7 PL and 0.9 PL at the depth of 0-15 cm and so the effect of the soil water content was not significant on the draft force of these tools.

The effect of bend angle was significant on draft force of the dual bent blade subsurface tillage tool at probability level of 1% (Table 2). The average of the draft force was significantly more at the bend angle of 20° compared with 10° and increasing the bend angle from 10° to 20° the draft force increased 23% (Table 3) which was in line with the results of Harrison and Licsko (1989). They stated that the draft force of bent leg tillage tool was increased with increasing bend angle from 30° to

45°. Due to equal work width of the tillage tools, the contact surface of tools with soil increased with increasing bend angle that eventually led to increase in friction and draft force of the tools. Another reason for the increase in draft force with increasing bend angle was more force requirements to lift the soil in more bend angle.

Table 2 ANOVA of the measured factors

Source of variation	df	Means of squares		
		Draft force, kN	Soil disturbance area, cm^2	Specific draft, kN m^{-2}
Moisture (a)	1	0.0088^{ns}	33867.18^{ns}	109.2^{ns}
Moisture error	4	0.468	14396.85	160.21
Tillage tool type (b)	1	6.431^{**}	146854.68^{**}	78.5^{ns}
Bend angle (c)	1	9.433^{***}	4504.6^{ns}	838.34^{**}
Rake angle (d)	1	33.483^{***}	1359123.52^{**}	4.44^{ns}
a×b	1	0.983^{ns}	71379.18^{ns}	63.02^{ns}
a×c	1	0.0099^{ns}	37018.52^{ns}	153.36^{ns}
a×d	1	0.977^{ns}	47691.02^{ns}	652.68^{*}
b×c	1	0.159^{ns}	5187.52^{ns}	30.72^{ns}
b×d	1	1.006^{ns}	16613.52^{ns}	52.92^{ns}
c×d	1	2.837^{*}	82419.18^{*}	1008.33^{**}
a×b×c	1	0.245^{ns}	25254.18^{ns}	223.6^{ns}
a×b×d	1	0.0247^{ns}	143.52^{ns}	3.63^{ns}
b×c×d	1	0.412^{ns}	38363.59^{ns}	418.9^{ns}
a×b×c×d	2	0.1505^{ns}	86849.1^{**}	169.82^{ns}
Error	28	0.498	11441.73	110.5
CV (%)	-	16.15	12.12	20.65

Note: ns: not significant, * and **: significant in probability levels of 5% and 1%, respectively.

The effect of rake angle on draft force was significant at probability level of 0.1% (Table 2). By increasing the rake angle from 7.5° to 15°, the draft force significantly increased as much as 48% (Table 3). Payne and Tanne (1959), and McKyes and Maswaure (1997), also revealed that smaller rake angle led to less draft force. Majidi and Raoufat (1997) also observed the least draft force at rake angle of 7.5° for bent leg tillage tool. Increasing rake angle, the dual bent blade subsurface tillage tool became closer to the vertical surface and the area of the blade image at vertical level increased that led to increase in the friction force. Also in this case the tool compressed more volume of the soil resulted in enhancing the draft force of the tillage tool.

The effect of tool type was significant on the draft force ($P \leq 0.01$) (Table 2). The mean comparison showed that the draft force of the forward dual bent blade subsurface tillage tool was significantly as much as 17.5% more than backward type (Table 3). One of the reasons that there is a significant difference between the two types of forward and backward tillage tools was the sooner contact of the blades in forward type that led to grater soil wedge than the contact of the blade tip of the backward type that thereby increasing the amount of soil failure and the surcharge force, and ultimately increased the draft force in forward type compared to backward type. Increasing the volume of soil failure in forward tillage tool compared to backward type and forming a small wedge in front of the backward type shank (that led to decline the surcharge force) resulted in decreasing in draft force of this type compared to forward type tillage tool (Figure 4).

Table 3 Mean comparison of draft force in dual bent blade subsurface tillage tool in different levels of experimental factors

	Draft force, kN
Tillage tool type	
forward	4.7^{a}
backward	4.0^{b}
bend angle	
10	3.9^{b}
20	4.7^{a}
Rake angle (°)	
7.5°	3.5^{b}
15°	5.2^{a}

Note: Mean of each experimental variable that have the same letters (a, b) have no significant differences based on LSD test at 5% probability level.

Direction of work

a. Forward b. Backward

Figure 4 Soil failure in the contact moment of dual bent blade subsurface tillage tool

The interaction between rake and bend angles was significant on the draft force at probability level of 5% (Table 2). Increasing the rake angle from 7.5° to 15°, the draft force of the tillage tools significantly increased at any levels of bend angle. The draft force of tillage tools in rake angle of 15 °significantly increased by increasing the bend angle from 10 ° to 20 ° but there was no significant difference in the rake angle of 7.5 ° (Figure 5). The least draft force was occurred at the rake angle of 7.5 ° and bend angle of 10 °(Figure 5).

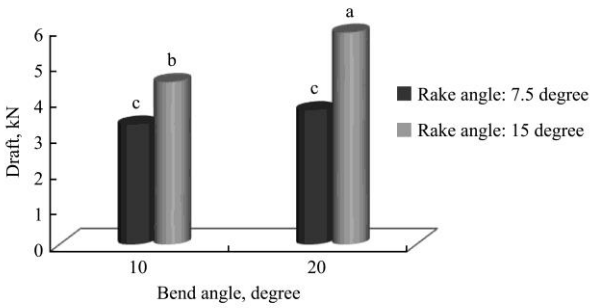


Figure 5 Interaction between rake and bend angle on the draft force of dual bent blade subsurface tillage tool.

3.1 Soil disturbance area

The ANOVA showed that the effect of moisture content was not significant on the soil disturbance area (Table 2). Decreasing the soil moisture, the soil disturbance area was a little decreased but not significantly that indicated the easier distribution of soil in upper moisture. But Sharifat and Kushwaha (1999) stated that soil disturbance area was affected by the soil moisture content. Differences in the soil disturbance area were due to the differences in soil failure type. The soil failure path was perpendicular to the direction of the tool travel in dual bent blade tillage tool (Figure 3) while the failure route in simple blades was in direction of the tool travel. The effect of tillage tool type was significant on soil disturbance area at probability level of 1% (Table 2). The disturbance area in forward type was significantly more than backward type as much as 13% (Table 4).

As it was shown in Table 2, the effect of bend angle on the soil disturbance area was not significant. The effect of rake angle of dual bent blade tillage tool was significant on the soil disturbance area at probability level of 0.1% (Table 2). Increasing the rake angle from 7.5 ° to 15 °the amount of soil disturbance area increased as much as 47% (Table 4). The soil disturbance area increased due to increase in the vertical image surface of the blade as a result of blade rake angle enhancement. Payne and Tanne (1959), and McKyes and Maswaure (1997) indicated that the changes in rake angle had no significant impact on the soil failure area but Majidi Iraj and Raoufat (1997), and Durairaj and Balasubramanian (1997) showed that the effect of rake angle was significant on the soil disturbance area at bent leg tillage tool and the most disturbance area occurred at the rake angle of 15 °. The difference in the results could be because of the tools geometry and specially the size of the tools which was smaller in the first group of researches than the second one.

Table 4 Mean comparison of soil disturbance area in dual bent blade subsurface tillage tool in different levels of experimental factors

	Soil disturbance area, cm^2
Tillage tool type	
forward	937[a]
backward	827[b]
Rake angle	
7.5	714[b]
15	1050[a]

Note: Mean of each experimental variable that have the same letters (a, b) have no significant differences based on LSD test at 5% probability level.

The interaction between soil moisture content and tillage tool type was significant on the soil disturbance area ($P \leq 0.5$) (Table 2). Soil disturbance area in forward type and the soil moisture of 0.9 PL was significantly more than backward type but in moisture content of 0.7 PL there was no significant difference between the tools (Figure 6). The interaction between rake and bend angles was also significant on the soil disturbance area at probability level of 5% (Table 2). Increasing the rake anfle from 7.5 ° to 15 °, the soil disturbance area was significantly increased for any level of bend angle (Figure 7).

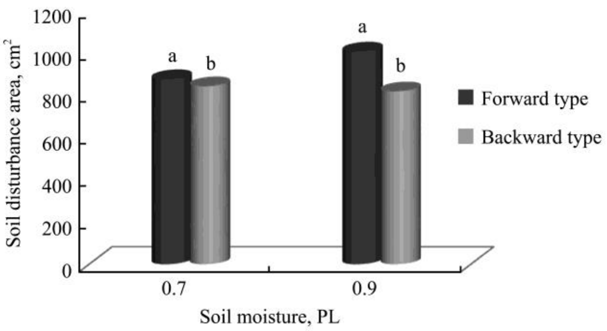


Figure 6 Interaction between soil moisture and tillage tool type on the soil disturbance area

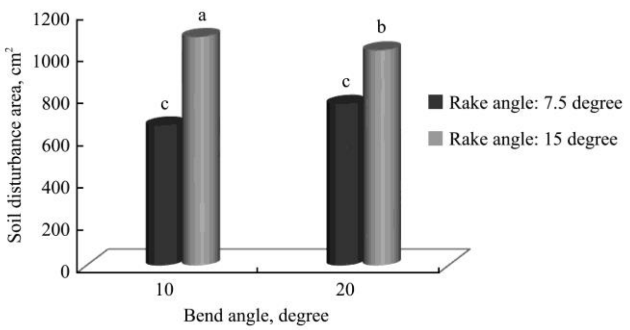


Figure 7 Interaction between rakes and bend angles on the soil disturbance area

3.2 Specific draft

The ANOVA indicated that the effects of soil moisture, tillage tool type, and rake angle was not significant on the specific draft of dual bent blade subsurface tillage tool (Table 2). The effect of bend angle was significant on the draft of the tillage tool at probability level of 1% (Table 2). Increasing bend angle from 10° to 20°, the tool specific draft significantly increased as much as 18% (Table 5). It should be noted that the effect of bend angle was not significant on the soil disturbance area (Table 2) but the draft force significantly increased with increasing the bend angle (Table 3) and resulted in increasing in specific draft.

Table 5 Mean comparison of the effect of bend angle on specific draft in dual bent blade subsurface tillage tool

Bend angle, degree	Specific draft, kN m^{-2}
10°	46.7^{b}
20°	55.1^{a}

Note: Mean of each experimental variable that have the same letters (a, b) have no significant differences based on LSD test at 5% probability level.

The soil disturbance area and draft force was more in the forward tillage tool than backward type but the specific draft in both types was approximately the same. Payne and Tanne (1959) reported that the specific draft of sub-soiler was increased by increasing the rake angle from 20° to 60°. But Majidi Iraj and Raoufat (1997), and Durairaj and Balasubramanian (1997) indicated that the rake angle had no effect on the specific draft.

The interaction between the soil moisture content and the blade rake angle was significant on the specific draft of dual bent blade subsurface tillage tool at probability level of 5% (Table 2). There was no significant difference in specific draft for both soil moisture levels by increasing the rake angle. Increasing the soil moisture from 0.7 PL to 0.9 PL, the specific drat was significantly decreased for the rake angle of 15° but there was no significant difference for the rake angle of 7.5° (Figure 8).

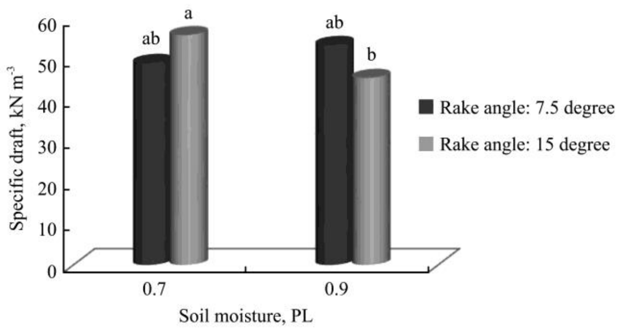


Figure 8 Interaction between rake angle and the soil moisture on the specific draft of dual bent blade subsurface tillage tool

The interaction between rake and bend angles was significant on the specific draft of the tillage tools at probability level of 1% (Table 2). Increasing the rake angle, the specific draft significantly decreased for the bend angle of 10° and there was no significant difference for the bend angle of 20°. Increasing the bend angle, the specific draft significantly increased for the rake angle of 15° but there was no significant difference for the rake angle of 7.5° (Figure 9).

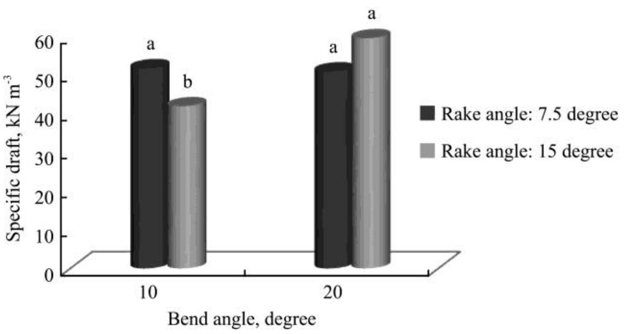


Figure 9 Interaction between the rakes and bend angles on specific draft of dual bent blade subsurface tillage tool

4 Conclusions

1) The changes in soil moisture had no significant effect on any measured variables of subsurface tillage tools.

2) The draft force was increased as much as 48% by increasing the rake angle of subsurface tillage tools from 7.5° to 15°. The minimum of draft force was occurred in backward type subsurface tillage tool with bend angle of 10° and rake angle of 7.5°.

3) Increasing the rake angle from 7.5° to 15°, the soil

disturbance area was significantly increased as much as 47%.

4) The soil specific draft significantly increased as much as 18% by increasing the bend angle from 10° to 20°.

5) The draft force and soil disturbance area in forward type was more than backward type because the number of contact points to soil was more in forward type.

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